



UNIVERSITI PUTRA MALAYSIA

**SIMULATION OF DISPERSION OF AIR POLLUTANTS
AND ACIDIC PRECIPITATION**

CHOONG WEI YEE

FK 1999 32

**SIMULATION OF DISPERSION OF AIR POLLUTANTS
AND ACIDIC PRECIPITATION**

CHOONG WEI YEE

**MASTER OF SCIENCE
UNIVERSITI PUTRA MALAYSIA**

1999



**SIMULATION OF DISPERSION OF PLUME AND
ITS RELATION TO ACIDIC PRECIPITATION**

By

CHOONG WEI YEE

**Thesis Submitted in Fulfilment of the Requirements for the
Degree of Master of Science in the Faculty of Engineering
Universiti Putra Malaysia**

May 1999



ACKNOWLEDGEMENTS

With utmost respect to Associate Professor Dr. Tan Ka Kheng, who has provided immeasurable support, invaluable guidance and generous advice throughout these hectic months. In his mild manners and unassuming ways, he has indeed been a source of inspirations. Thank you !

With deepest appreciation to the Encik Azman, Encik Pauzi Zakaria, Dr Cai Xiao Ming and Tan Kah Yaw who had gone above and beyond all expectation in their kind assistance. Their generosity with their valuable time and knowledge is truly admirable.

Heartfelt appreciation to Lai for his continued support and for being an example of selfless giving, Thanks too to Ng, Tee and Clarice for their endless support and assistance.

And with love and appreciation to my family for their immense support and making me what I am today. Thank you !

TABLE OF CONTENTS

	ACKNOWLEDGEMENTS.....	Page ii
	LIST OF TABLES.....	v
	LIST OF FIGURES.....	vii
	ABSTRACT.....	xi
	ABSTRAK.....	xiii
CHAPTER		
I	INTRODUCTION.....	1
	Global Context.....	2
	Malaysian Context.....	3
	Significance of Study.....	4
	Objective.....	5
II	LITERATURE REVIEW.....	6
	Introduction.....	6
	Formation of Cloud and Rain in Hilly Terrain.....	7
	Chemistry of Acid Rain.....	12
	Sulphates.....	12
	Nitrates.....	18
	Dispersion and Deposition Mechanism.....	20
	Introduction.....	20
	Meteorological Factors.....	20
	Dispersion of Plume.....	31
	Wet Deposition Mechanism.....	33
	Cloud and Fog Water Chemistry.....	38
	Effects of Acid Rain.....	43
	Effect on Soil.....	43
	Effect on Forest.....	45
	Effect on Human Health.....	50
	Simulation of the Dispersion of Pollutants.....	51
	Gaussian Plume Model.....	58
	Conclusion.....	61
III	METHODOLOGY.....	65
	Chemical Characterization of Rain.....	65
	Simulation of Dispersion of Plume from a Stack	
	Using FLUENT.....	66
	Settings of Simulation.....	68



	Transformation of Gaseous SO_2 to SO_4^{2-} and NO_2 to NO_3^-	78
IV	RESULTS AND DISCUSSIONS	81
	Chemical Characterization of Precipitation.....	83
	Precipitation Characterization for Hilly Terrains...	83
	Comparison of Precipitation Characterization with Low-lying Areas.....	98
	Comparison to Precipitation Characterization with a Polluted Area.....	105
	Simulation of Dispersion from an Incinerator Stack.....	110
	Introduction.....	110
	Comparison to Gaussian Dispersion Model.....	111
	Effect of Wind Velocities in an Open Area.....	124
	Simulation with Different Wind Velocity in the Presence of a Hill.....	138
	Introduction.....	138
	Comparison between the Different Wind Velocity for both SO_2 and NO_2 in a Hilly Terrain.....	139
	pH of the Fog/Rain Water and Deposition Flux.....	156
	Introduction.....	156
	pH of the Fog/Cloud and Rainwater, and Deposition Flux in an Open Area.....	157
	pH of the Fog/Cloud and Rainwater, and Deposition Flux in the Presence of a Hill.....	162
	Comparison between an Open Area and in the Presence of a Hill.....	164
V	CONCLUSIONS	167
	BIBLIOGRAPHY	172
	APPENDIX	180
	A Gaussian Distribution Model.....	181
	B Case Settings.....	236
	VITA	252

LIST OF TABLES

Table		Page
2.1	Properties of Atmospheric Aqueous Particles and Drops.....	12
2.2	Meteorological Conditions Defining Pasquill Turbulence Dispersion Class.....	27
2.3	Sensitivity to Acid Precipitation Based Buffer Capacity Against pH Change, Retention of H^+ and Adverse Effect on Soils.....	45
2.4	Air Pollutants Effects on Forest Tree.....	49
2.5	Effects of Air Pollutants on Human Health.....	51
3.1	Study Areas for Chemical Characterization of Precipitation....	66
3.2	Physical Properties of Ambient and Plume Phase.....	72
3.3	Underrelaxation Factors for All Cases Run.....	75
4.1	Mean Concentrations in $\mu\text{eq/l}$ of the Major Chemical Components in Precipitation.....	85
4.2	Concentrations of Anions and Cations in Precipitation.....	88
4.3	Ratio of Total Acidity to Free Acidity in Precipitation.....	90
4.4	Maximum Possible Contribution of SO_4^{2-} , NO_3^- , Cl^- and F^- to Free Acidity of Precipitation.....	93
4.5	Matrix of Correlation Coefficients (r) Among Chemical Components in Precipitation for Hilly Sites.....	96
4.6	Comparison of Anion Deficit due to Organic Acid between Hilly and Low Lying Areas.....	102
4.7	Matrix of Correlation Coefficients (r) Among Chemical Components in Precipitation for Low Lying Areas.....	103
4.8	Matrix of Correlation Coefficients (r) among Chemical Components in Precipitation for Polluted Area.....	109

4.9	Comparison of Concentration of SO ₂ between Simulated Value for Various Atmospheric Stability Class.....	114
4.10	Comparison between Theoretical and Simulated Values of SO ₂ at Groundlevel and at Height 30 m	116
4.11	Comparison between Concentration Profile at Groundlevel under Different Wind Velocities.....	135
4.12	Calculated pH values for Fogwater and Rainwater in Open Area and in the Presence of a Hill under Varying Wind Velocity.....	158
4.13	Contribution of NO ₂ , SO ₂ and CO ₂ to the Calculated pH Values for Fog and Rain Droplets.....	160
4.14	Contact Time and Penetration Depth for Different Rain Droplet Size.....	161

LIST OF FIGURES

Figure		Page
2.1	The Effect of Surface Roughness on Wind Velocity.....	22
2.2	Correlations for σ_z Based on the Pasquill Stability Classes A -F.....	26
2.3	Correlations for σ_y Based on the Pasquill Stability Classes A - F.....	26
2.4	Determination of Afternoon Mixing Height from Morning Upper-air Sounding and Afternoon Surface Temperature...	28
2.5	Wind Flow Pattern Around a Building under Typical Conditions of Atmospheric Stability and Wind Velocity (a) Side View and (b) Plane View.....	30
2.6	Changes in Carbon (or Energy) Available for Defense and Repair During Stages of Decline.....	48
2.7	Three Dimensional Concentration Profiles of a Nonrising Point Source and Centreline of a Rising Plume for Dispersion Calculation at Distance x	60
3.1	Grid Cell for an Open Area.....	70
3.2	Grid Cell for a Hilly Terrain.....	70
3.3	Overview of the Solution Process in Fluent.....	77
3.4	Transformation Process of SO_2 to SO_4 and NO_2 to NO_4	78
4.1	Yearly pH Distribution for Peninsular Malaysia for 1995...	82
4.2	Location of the Study Areas for the Hilly Sites and their Low-lying Adjacent Sites.....	84
4.3	Temporal Variation of pH Precipitation for Hilly Sites.....	86
4.4	Ratio of Cations to Anions of Precipitation Samples for Hilly Sites.....	92

4.5	Temporal Variation of pH Precipitation for Low-lying Areas.....	99
4.6	Ratio of Cations to Anions of Precipitation Samples for Low-lying Areas.....	100
4.7	Temporal Variation of pH Precipitation for a Polluted Area.....	106
4.8	Ratio of Cations to Anions of Precipitation Samples of a Polluted Area.....	107
4.9	Normalized Residual for the Simulation Carried Out.....	112
4.10	Concentration Profile.....	117
4.11	Concentration of SO ₂ vs Distance at Groundlevel with Wind Velocity of 2.45 m/s.....	118
4.12	Concentration of Plume and the Downwind Distance for Maximum Ground level Concentration with Wind Velocity of 2.45 m/s.....	118
4.13	Variation of SO ₂ with Distance at Height 25 m.....	119
4.14	Density of Plume.....	120
4.15	Bend-over Plume and Effective Plume Height.....	121
4.16	Velocity Vector of the Ambient Phase.....	123
4.17	Normalised Residuals for SO ₂ under Different Wind Velocities (a)1.2 m/s and (b) 2.45 m/s	125
4.18	Normalised Residuals under Different NO ₂ for Wind Velocities (a)1.2 m/s and (b) 2.45 m/s.....	126
4.19	Density of Plume for SO ₂ under Different Wind Velocities (a)1.2 m/s and (b) 2.45 m/s.....	128
4.20	Density of Plume for NO ₂ under Different Wind Velocities (a)1.2 m/s and (b) 2.45 m/s.....	129

4.21	Effective Plume Height and Concentration of SO ₂ for Wind Velocities (a) 1.2 m/s and (b) 2.45 m/s.....	131
4.22	Effective Plume Height and Concentration of NO ₂ for Wind Velocities (a) 1.2 m/s and (b) 2.45 m/s.....	132
4.23	Concentration Profile of SO ₂ under Different Wind Velocities (a) 1.2 m/s and (b) 2.45 m/s.....	133
4.24	Concentration Profile of NO ₂ under Different Wind Velocities (a) 1.2 m/s and (b) 2.45 m/s.....	134
4.25	Ambient Velocity Vector under Different SO ₂ under Different Wind Velocities (a) 1.2 m/s and (b) 2.45 m/s.....	136
4.26	Ambient Velocity Vector for NO ₂ under Different Wind Velocities (a) 1.2 m/s and (b) 2.45 m/s.....	137
4.27	Normalised Residuals for SO ₂ in the Presence of a Hill under Different Wind Velocities (a) 1.2 m/s and (b) 2.45 m/s.....	140
4.28	Normalised Residuals for NO ₂ in the Presence of a Hill under Different Wind Velocities (a) 1.2 m/s and (b) 2.45 m/s.....	141
4.29	Density of Plume for SO ₂ in the Presence of a Hill under Different Wind Velocities (a) 1.2 m/s and (b) 2.45 m/s.....	142
4.30	Density of Plume for NO ₂ in the Presence of a Hill under Different Wind Velocities (a) 1.2 m/s and (b) 2.45 m/s.....	143
4.31	Plume Behaviour over a Isolated Round Hill as the Approach Flow Becomes More Stable.....	144
4.32	Plume Concentration for SO ₂ in the Presence of a Hill under Different Wind Velocities (a) 1.2 m/s and (b) 2.45 m/s.....	145
4.33	Plume Concentration for NO ₂ in the Presence of a Hill under Different Wind Velocities (a) 1.2 m/s and (b) 2.45 m/s.....	147

4.34	Ambient Velocity Vectors for SO ₂ in the Presence of a Hill under Different Wind Velocities (a) 1.2 m/s and (b) 2.45 m/s.....	148
4.35	Ambient Velocity Vectors for NO ₂ in the Presence of a Hill under Different Wind Velocities (a) 1.2 m/s and (b) 2.45 m/s.....	149
4.36	Plume Concentration for SO ₂ at the Windward Side of a Hill under Different Wind Velocities (a) 1.2 m/s and (b) 2.45 m/s.....	150
4.37	Plume Concentration for NO ₂ at the Windward Side of a Hill under Different Wind Velocities (a) 1.2 m/s and (b) 2.45 m/s.....	151
4.38	Ambient Velocity Vectors for SO ₂ at the Windward Side of a Hill under Different Wind Velocities (a) 1.2 m/s and (b) 2.45 m/s.....	152
4.39	Ambient Velocity Vectors for NO ₂ at the Windward Side of a Hill under Different Wind Velocities (a) 1.2 m/s and (b) 2.45 m/s.....	153
4.40	Concentration profile of SO ₂ in the Presence of a Hill under Different Wind Velocities (a) 1.2 m/s and (b) 2.45 m/s.....	154
4.41	Concentration profile of NO ₂ in the Presence of a Hill under Different Wind Velocities (a) 1.2 m/s and (b) 2.45 m/s.....	155

Abstract of thesis presented to the senate of Universiti Putra Malaysia in partial fulfilment of the requirements for the degree of Master of Science

SIMULATION OF DISPERSION OF AIR POLLUTANTS AND ACIDIC PRECIPITATION

By

CHOONG WEI YEE

May 1999

Chairman: Associate Professor Tan Ka Kheng, Ph.D., P. Eng.

Faculty: Engineering

Acidic precipitation poses a threat to ecosystems. Many countries in Europe and northeastern parts of the United States of America have experienced forest decline in their mountainous region due to acidic deposition. Malaysia, being a rapidly industrialised nation, succumbed to acidic precipitation too. This study sought to determine the trend of acidic precipitation in Malaysia, particularly in hilly terrain, and to investigate the significance of building an incinerator near a hill.

Wet fallout data for 1996 for three hilly sites were collected. These data were analysed statistically and compared to the data of low-lying areas nearest to the hill sites, and also to a polluted area. Numerical simulations on the dispersion of plume from an incinerator were carried out using a commercial software FLUENT to determine the flow pattern of the plume and its effect on the hill. Simulations were

carried out for two scenarios that were for an incinerator located in an open area, and the other located near to a hill.

Results of this study indicated that the studied hill sites received acidic precipitation at an average of 40% for 1996, with an average annual pH of 5.0. This reflected that the tropical forest in these hilly sites has a high potential risk of exposure to acidic precipitation which could be detrimental to them. Results from the simulation showed that the plume emitted by the incinerator has the most significant impact on the leeward side of the hill, whereby the calculated pH of rainwater here was typically around 2. In the case of an open area, the pH of the rainwater was typically around 3 - 4. The calculated pH of the fog/cloud water was found to be two to three order more acidic compared to rainwater. This indicated that the forest in a highland area, which is usually surrounded by high moisture content in the atmosphere, may receive high acidic deposition due to its contact with the fog/cloud. However, the sulphate deposition flux calculated in this study was well below the allowed load of 20 kg/ha.yr.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Master Sains

**SIMULASI PENYERAKAN BAHAN PENCEMAR UDARA
DAN HUJAN ASID**

Oleh

CHOONG WEI YEE

Mei 1999

Pengerusi: Profesor Madya Tan Ka Kheng, Ph.D., P.Eng.

Fakulti: Kejuruteraan

Fenomena hujan asid sememangnya mengancam ekosistem. Banyak negara di Eropah dan juga di kawasan timur-laut Amerika Syarikat telah dilaporkan mengalami masalah kemerosotan hutan akibat kejadian hujan asid. Kajian ini dijalankan bertujuan untuk menentukan corak aliran fenomena hujan asid di Malaysia, terutamanya di kawasan bukit-bukau and juga untuk megkaji kesan pelepasan asap dari sebuah insinerator yang terletak berhampiran dengan sebuah bukit.

Data air hujan bagi tahun 1996 bagi tiga kawasan bukit telah dikumpulkan. Data ini kemudiannya telah dianalisisakan mengikut kaedah statistik dan dibandingkan dengan data daripada kawasan tanah rendah yang terdekat dengan

juga dengan sebuah kawasan yang mengalami pencemaran udara yang serius. Kerja simulasi yang menggunakan perisian FLUENT juga telah dijalankan untuk menentukan corak aliran asap pelepasan dan juga kesannya terhadap sebuah bukit. Simulasi telah dijalankan bagi dua senario yang mana senario pertama melibatkan simulasi dengan kawasan lapang dan senario kedua melibatkan kawasan berbukit.

Keputusan daripada kajian ini menunjukkan bahawa kawasan bukit yang dikaji mengalami kejadian hujan asid dengan purata 40% bagi tahun 1996, dengan purata pH bernilai 5. Oleh itu, kawasan hutan tropika di kawasan bukit yang dikaji mempunyai risiko yang tinggi dari segi pendedaannya kepada kelembapan yang berasid. Pendedahan kepada kelembapan berasid boleh mudaratkan pertumbuhan pokok di kawasan tersebut. Keputusan dari kerja simulasi juga menunjukkan bahawa asap pelepasan dari insinerator membawa kesan yang paling ketara kepada bahagian belakang angin bukit, yang mana nilai pH yang dikira bagi air hujannya adalah sekitar 2. Bagi senario kawasan lapang, nilai pH bagi air hujannya adalah sekitar 3 - 4. Nilai pH yang dikira bagi kelembapan dalam kabus/awan didapati adalah dua hingga tiga kali lebih berasid daripada air hujan. Ini menunjukkan bahawa kawasan hutan tropika di kawasan tanah tinggi, yang sering dikelilingi oleh kadar kelembapan yang tinggi sepanjang tahun, kemungkinan menerima lebih banyak kelembapan yang berasid akibat pendedahan secara langsung terhadap kelembapan yang berasid ini. Namun demikian, kadar deposasi sulfat dalam kajian ini masih dalam lingkungan kadar optimum sebanyak 20 kg/ha setahun.

CHAPTER I

INTRODUCTION

The natural acidity of rainwater is often taken to be pH of 5.6 which is that of pure water in equilibrium with the global atmospheric concentration of carbon dioxide CO₂ (330 ppm) and this pH values of 5.6 has been used as the demarcation line for acidic precipitation (Bubenick, 1984). Hence, the term acid rain has come to mean rainfall with a pH of less than 5.65. Any rainfall with a pH of 5.00 and below is deemed to have anthropogenic sources of acidity.

The acid content of rain in many parts of the world has steadily risen over the years as countries became more industrialised and increased their use of fossil fuels. These fuel, oil and coal release to the environment high concentrations of sulfur and nitrogen oxides, precursors of strong acids when burned. The oxides are transformed by chemical and physical processes occurring in the atmosphere, in the soil and in lakes and streams to compounds that may degrade the environment. The transformation processes involving the pollutant oxides are complex and may involve both homogeneous and heterogeneous paths to the resulting strong acids.

Acidity is undesirable because:

- Acidity gives water a greater capacity to attack geological materials, it accelerates rock weathering and so it is usually accompanied by high total dissolved solids (TDS) including hardness;
- Acidity increases the solubility of hazardous substance such as aluminium (Al), and is corrosive and toxic to fish and other aquatic forms;
- Acidity limits the use of water without extensive treatment due to high total dissolved solids (TDS), high metal content and low pH. This often requires that acid waters be diluted, as well as neutralised.

Global Context

Increasing attention has been given to the exposure of highland forests to atmospheric pollutants because of the possible link between the sensitivity of highland forests and the effect of air pollutants onto them. There is evidence that acid rainfall, as a by-product of energy-related activities, is introducing a considerable stress on both rural and urban areas of the United States of America and Western Europe. Studies carried out by several researchers such as Overton and Aneja (1979), Lovcett et al. (1990), Saxena and Lin (1990), Chaumerliac et al. (1990), Raynal (1992) and Johnson et al. (1992) have linked the forest decline to acidic deposition. Researchers have postulated acidic precipitation as one of the main factor for forest decline in Germany, Europe and north-eastern of North America. In Germany, the 1994 inventory indicated severe (> 25% defoliation)

damage of about 25% of all trees. In Germany at present, oak stands have the highest degree of visible damage with about 30 – 40% of the trees with severe defoliation. The forest inventory of 1993 in 27 European countries and 4800 sites, evaluating more than 100 000 trees, revealed 23% of all trees in damage class 2 – 4 (defoliation > 25%). The highest degree of damage was found in Central Europe, namely in Poland, Czech Republic, Slovakia and Germany regions suffering from a relatively high level of air pollutants.

It is widely acknowledged that acidic atmospheric deposition can cause soil acidification, leading to nutrient deficiency as a result of leaching of important nutrients such as calcium (Ca), magnesium (Mg) and potassium (K). Furthermore, acidity also cause metal toxicity particularly aluminium (Al) and reduction in tree growth.

Malaysian Context

In Malaysia, acidic atmospheric deposition has been recorded in urban towns such as Klang Valley, Butterworth and Johor Bahru with pH reading reaching 4.0 since 1990. It should be noted here that $\text{pH} < 5.0$ reflects the influence of anthropogenic sources. Data obtained from Malaysia Meteorological Services (MMS) indicated that wet acidic deposition has been observed in highland areas

such as Cameron Highlands and Bukit Kledang with pH dipping below 5.0 at certain times of the year. These data reflect that Malaysia is experiencing the acid rain phenomena.

Malaysia being a tropical country has relatively high humidity (> 80%) throughout the year. Forced uplift of moist air over hills or mountains would lead to the formation of fogwater and cloud or a phenomena known as orographic precipitation (Lovett and Kinsman, 1990). As air mass rises over a topological barrier, it expands and cools because of decreased air pressure, forming upslope fogs or clouds. This in turn could lead to the rainout process. As the air mass cools, condensation occurs followed by droplets growth during which various pollutants such as sulphur dioxide (SO₂), nitric acid (HNO₃) dissolve in the droplets, undergo chemical changes and fallout as precipitation. Hence, the forest canopy will be likely to receive the wet acidic deposition due to the occurrence of orographic precipitation and the presence of the moist fog and cloud surrounding the highlands.

Significance of Study

To date, very few studies have been carried out to study the effect and extent of acidic deposition on the tropical highland forest in Malaysia. This study will seek to investigate the cause-effect relationship between the pollutant emission from

individual stack and the measured acidity of precipitation at receptor areas, in this case the highland area. It is hope that this study would be able to provide some information on the significance of having a stack built near a hill.

Simulations of dispersion of air pollutants in hilly terrain and in an open area have been carried out. It is hope that the simulation work carried out would be able to enhance the understanding of the dynamics (emission, transport, transformation) of air pollution as a system. Models can have an important role to play in the development of environmental policies aimed at containing and controlling long range transboundary air pollutant transport. Dispersion models for atmospheric pollutants are useful decision support systems for air pollution management. Increasingly, these models are being used to generate inputs to specific catchment areas in environmentally sensitive regions for past, present or future patterns of emissions throughout Europe (Metcalf et. al., 1989; Costa et al., 1996). Hence, they are ideal complement to air quality control networks.

Objective

The objectives of this study are:

1. To determine the trend of acidic precipitation in Malaysia;
2. To identify the impact of plume from a stack onto an open area and to a nearby hill through numerical simulation.

CHAPTER II

LITERATURE REVIEW

Introduction

Precipitation removes gases and particles from the atmosphere by two processes:

□ **rainout**

- which is the incorporation of material into cloud drops that grow in size sufficiently to fall to the ground. Water vapour condensed on cloud condensation nuclei and many of these nuclei are believed to be sulphate particles that have been formed as a result of the gas-to-aerosol conversion of natural and man-made sulphur dioxide emissions. Condensation is followed by droplet growth, during which various pollutants dissolve in the droplets, undergo chemical changes and begin their descent to the ground in falling precipitation.

□ **washout**

- which occurs when material below the cloud is swept out by rain or snow as it falls. The washout of SO₂ by rain falling through a uniform

concentration of SO_2 is a function of the size spectrum of droplets, the initial pH of the rain, height of the SO_2 concentration and the absolute magnitude of the SO_2 concentration. Presence of ammonia (NH_3) hastens the absorption of SO_2 and its conversion to sulphates. In his study, Marsh (1978) concluded that the scavenging of SO_2 gas and particulate below cloud base and in-cloud scavenging contribute about equally to the concentration of sulphates in precipitation.

Together, these two processes account for wet deposition of acidic material on the earth's surface.

Precipitation acidity is primarily attributed to the strong minerals acids such as sulphuric acid (H_2SO_4) and nitric acid (HNO_3). The immediate precursors of these acids are the man-made and naturally produced gases sulphur oxides, SO_x (SO_2 and SO_3) and nitrogen oxides, NO_x (NO and NO_2). Natural sources of SO_x and NO_x are generally distributed globally whereas anthropogenic emissions tend to be concentrated regionally near population centres

Formation of Cloud and Rain in Hilly Terrain

Air moving over or around hilly or mountainous terrain often influences cloud formation. For example, mountain ranges are typically preferred locations for fog, stratus, stratocumulus, cumulus and cumulonimbus and valleys between

mountains often favour fog occurrence. Orographic cloud occurs due to the cooling of an air mass as it rises to cross ground which is higher than that over which it has been travelling. As the air mass rises and cools, the water vapour reaches saturation point and water starts to condense out on suitable aerosol particles or foliage. As the air mass continues to rise, further cooling occurs, condensation continues and scavenging of gaseous species by the water droplets takes place (Hough, 1983).

When such air has completed its ascent, its path will continue to be controlled by the terrain over which it flows. For a plateau, or for transverse motion across a series of closely spaced ridges, the air will move at an approximately constant altitude with constant liquid water content. If however, the land slopes downwards with no further high ground in the near distance, then the air will descend. On descending, the cloud will evaporate due to the warming of the air and a reverse of the processes discussed above will occur.

Orographically induced flow is able to produce or influence precipitating clouds through the following mechanisms:

□ **Seeder-Feeder Mechanism over Small Hills**

- Convective cells aloft can produce large precipitation particles, which upon falling through a lower cloud layer, grow at the expense of the water content of the lower cloud. By itself, the low-level cloud might not precipitate. Precipitation particles from the upper cloud collect cloud particles from the low cloud and the water collected is then deposited on the ground.

❑ **Upslope Condensation**

- If the air forced over a mountain is sufficiently moist through a large portion of the lifted layer, condensation may occur in upslope flow or wave clouds.

❑ **Orographic Convection**

- When air flowing over rugged terrain is potentially unstable, the lifting induced by the terrain can lead to the release of instability and eventually, precipitation (Houze, 1993).

The adiabatic ascent of moist air could cause condensation at certain elevations and thus produces clouds. Whenever fogs and mists occur with great frequency, as they do on windward mountain slopes in the condensation or 'cloud belt', they may constitute a significant source of additional moisture. Fog-borne moisture, dew and heavy mists may condense upon exposed vegetational surfaces and drip or run down stems to the ground. Such moisture quantity is known to be highly dependent upon both successional stage and foliage characteristics of the dominant vegetation (Stadmuller, 1987). The inherent vegetational characteristics are as follows:

- height of vegetation
- canopy structure (influencing the roughness thus causing micro turbulence)
- size, quantity, location and arrangement of leaves
- quantity, forms and types of epiphytes